FAILURE ANALYSIS OF FUEL INJECTION PUMPS FROM GENERATOR SETS FUELED WITH JET A-1

INTERIM REPORT
BFLRF No. 268

By

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The U.S. Department of Defense (DOD) has adopted the single fuel for the battlefield concept. Diesel fuel will be replaced by JP-8/Jet A-1 in compression ignition engines, thereby lowering the fuel logistics burden. These fuels have successfully undergone extensive testing in both the laboratory and in field trials. However, increased failure rates are being reported on a number of fuel-sensitive components during Operation Desert Shield in Saudi Arabia.

Five failed Stanadyne rotary fuel injection pumps were returned to the Belvoir Fuels and Lubricants Research Facility (BFLRF) at Southwest Research Institute (SwRI) for disassembly and post-failure analysis. Particular attention was given to the possible effects of low-lubricity fuel. The results of this investigation indicate that most of the failures may be attributed to causes other than poor fuel lubricity. The reason for failure of specific components in two of the pumps could not be conclusively determined. However, it is believed that they would not have occurred as a result of short-term operation with Jet A-1.

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EXECUTIVE SUMMARY

Problems and Objectives: To lower its fuel logistics burden, the Department of Defense (DOD) is advancing the use of a single fuel on the battlefield. To this end, JP-8/Jet A-1 is replacing diesel fuel (DF-2) in many applications. However, the decreased lubricity of these fuels combined with their low viscosity (compared to DF-2 diesel) is causing concern, particularly in relation to the premature failure of certain rotary fuel injection pumps.

Importance of Project: A large increase in the frequency of unplanned maintenance associated with Stanadyne rotary fuel injection pumps operating on Jet A-1 is reported from Operation Desert Shield. This component is vital to the reliable operation of many types of ground equipment. The completion of this study will determine the cause of failure in a number of pumps returned from Saudi Arabia.

Technical Approach: In this study, five failed Stanadyne pumps were examined. Little background information was available, other than that the pumps were used on diesel engine generator sets. The effect of fuel lubricity was masked by the fact that each pump has operated on both diesel and Jet A-1/JP-8 for an unspecified period of time. If the location of the failure was obvious (i.e., seizure), the pump was disassembled and the cause determined. Otherwise, the pump was placed on a test stand. The delivery was compared with the manufacturers specifications. After testing, each pump was completely disassembled. A pump specialist then subjectively rated the degree of wear present on critical components within the pump. This procedure allowed comparison among the pumps and also highlighted the more wear-sensitive areas within the pump design.

Accomplishments: The cause of pump failure was clear in each instance, and none could be directly attributed to the use of Jet A-1 in the generator sets. One pump failed due to binding of the transfer pump blades, while two of the pumps had grit or corrosion particles present within the mechanism. The most common cause of failure was fuel leakage past the metering valve while in the OFF position. The material loss due to wear appeared much less than the random variation in valve size from pump to pump. In one instance, no wear was visible on the metering valve assembly; however, the valve bore was considerably oversize, indicating a possible deviation from the correct tolerance during manufacture. The effects of poorly fitting valves is likely to be exacerbated by the use of Jet A-1/JP-8 due to the lower viscosity of these fuels.

Military Impact: The results of this study indicate that the pump failures were not directly related to the use of Jet A-1/JP 8. Some attrition is likely with all fuels, and the precise effects (if any) of Jet A-1/JP-8 could not be determined. From the present limited study, it would appear that other problems such as fuel cleanliness are of equal or greater importance than fuel lubricity.

FOREWORD/ACKNOWLEDGMENTS

This work was conducted at the Belvoir Fuels and Lubricants Research Facility (BFLRF) located at Southwest Research Institute (SwRI), San Antonio, TX, under Contract No. DAAK70-87-C-0043, during the period November 1990 through January 1991. The work was funded by U.S. Army Belvoir Research, Development and Engineering Center, Ft. Belvoir, VA, with Mr. T. C. Bowen (STRBE-VF), serving as the contracting officer's representative, and Mr. M. E. LePera, chief of Fuels and Lubricants Division (STRBE-VF), as the project technical monitor.

Technical expertise of BFLRF Technician Rodney Grinstead in disassembly, inspection, flow-bench, calibration, and diagnosis of fuel injection pumps is gratefully acknowledged. Since this effort was a fast-track response, it is also appropriate to acknowledge background assistance provided by Doug Yost and Bill Likos of the BFLRF engineering staff and Steve Westbrook of the BFLRF chemical laboratory staff. Special efforts of Esther Cantu, LuAnn Pierce, and Jim Pryor of the BFLRF documents processing group are also appreciated.

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I. INTRODUCTION AND BACKGROUND

The U.S. Department of Defense (DOD) has adopted the single fuel for the battlefield concept.(1-2)* The U.S. Army is converting its ground tactical fleet of diesel fuel-consuming vehicles/equipment in several overseas areas from diesel fuel to MIL-T-83133 JP-8.(3) The DOD and North Atlantic Treaty Organization (NATO) "single-fuel" directives are supported by many years of engine testing (4-6) and, more recently, by an ongoing JP-8 demonstration at Fort Bliss, TX.(7) There is significant concern within the U.S. Army/DOD concerning the use of JP-8 as an alternative fuel to No. 2 diesel fuel (DF-2).

Some deterioration in the performance of Stanadyne rotary fuel injection pumps (Model DB2) fitted to a General Motors (GM) 6.2-liter engine was observed in a 210-hour laboratory dynamometer test (8) and in a laboratory pump rig evaluation.(9) However, this deterioration was not evident in a subsequent 400-hour laboratory dynamometer test (10), nor in a 10,000-mile road test (11) with M1028 Commercial Utility Cargo Vehicles (CUCV) at the Mesa Arizona proving grounds. Concern regarding the use of Jet A-1 (12) fuel has recently surfaced in Operation Desert Shield. In particular, increased unplanned maintenance associated with the Stanadyne pump is claimed. The manufacturer identified and produced pump modifications much earlier to address low-viscosity fuel usage under arctic conditions.(9,11) However, the majority of pumps currently in service are of the standard type.

Five pumps reported to have failed in the field were forwarded for analysis to the Belvoir Fuels and Lubricants Research Facility at Southwest Research Institute. These pumps were removed from diesel engine driven (DED) mobile power generator sets. It should be recognized that these pumps may have operated on Jet A-1 fuel rather than JP-8. JP-8 includes a corrosion inhibitor additive, which may improve fuel lubricity. In addition, the lubricating qualities of a fuel are likely to be influenced by the amount and type of sulfur compound present. This sulfur compound varies as a function of crude source and normally ranges in levels between 0.2 and 0.4 mass%. TABLE 1 contains comparative properties associated with DF-2, JP-8, Jet A-1, DF-2, and DF-A fuels. The numbers shown in parentheses with "footnote B" in TABLE 1

* Underscored numbers in parentheses refer to the list of references at end of this report.

TABLE 1. Comparison of Selected Fuel Specification Requirements Related to Diesel and Turbine Engine Performance

Properties	VV-F-800D DF-A	VV-F-800D DF-1	VV-F-800D DF-2	VV-F-800D DF-2 (OCONUS)*	MIL-T-5624N JP-5/NATO Code F-44	MIL-T-83133C JP-8/NATO Code F-34	ASTM D 1655 Jet A-1/NATO Code F-35
Flash Point, °C, min	38	38	52	56	60	38	38
Cloud Point, °C, max	-51	**	**	13	NR†	NR	NR
Pour Point, °C	Rpt	Rpt	Rpt	18	NR	NR	NR
Freezing Point, °C, max	NR	NR	NR	NR	-46	-47	-47
Kinematic Viscosity at 40°C, cSt	1.1 to 2.4	1.3 to 2.9	1.9 to 4.1	1.3 to 5.0(A)	NR(1.50)(B)	NR(1.25)(B)	NR(1.25)(B)
Kinematic Viscosity at -20°C, cSt, max	NR	NR	NR	NR	8.5	8.0	8.0
Distillation, °C							
10% recovered, max	NR	NR	NR	NR	205	205	205
20% recovered, max	NR	NR	NR	NR	Rpt	Rpt	Rpt
50% recovered, max	Rpt	Rpt	Rpt	NR	Rpt	Rpt	Rpt
90% recovered, max	288	288	338	357	Rpt	Rpt	Rpt
End Point, max	300	330	370	370	290	300	300
Residue, vol%, max	3	3	3	3	1.5	1.5	1.5
Carbon Residue on 10% Bottoms, wt%, max	0.10	0.15	0.35	0.2	NR	NR	NR
Sulfur, mass%, max	0.25	0.50	0.50	0.30	0.40	0.30	0.30
Cu Corrosivity							
3 hr at 50°C, max	3	3	3	1	NR	NR	NR
2 hr at 100°C, max	NR	NR	NR	NR	1	1	1
Ash, wt%, max	0.01	0.01	0.01	0.02	NR	NR	NR
Accelerated Stability, mg/100 mL, max	1.5	1.5	1.5	1.5	NR	NR	NR
Neutralization Number, mg KOH/g, max	0.05	NR	NR	0.1	0.015	0.015	0.015
Particulate Contamination, mg/L, max	10	10	10	10	1.0	1.0	1.0
Cetane Number, min	40	40	40	45	NR(42.3)(B)	NR(44.9)(B)	NR(44.9)(B)
Net Heat of Combustion							
MJ/kg, min	NR	NR	NR	NR	42.6	42.8	42.8
Btu/gal.	NR	NR	NR(130,575)(B)	NR(127,776)(B)	NR(125,965)(B)	NR(123,138)(B)	NR(123,138)(B)
Corrosion Inhibitor, mg/L	NR	NR	NR	NR	QPL-25017	QPL-25017	NR
Antiicing Additive, vol%	NR	NR	NR	NR	0.15 to 0.20	0.10 to 0.15	NR

* Meets all requirements of NATO Code F-54 Guide Specifications.
** Specified according to anticipated low ambient temperature at use location.
† NR = No Requirement.
(A) Kinematic Viscosity values given are equivalent to NATO requirement of 1.8 to 9.5 cSt at 20°C.
(B) Average value from Reference No. 13 shown for comparison purposes.

are average values from an earlier survey (13) that are provided for comparison purposes. Fig. 1 shows a graphical representation of the boiling range of these fuels.

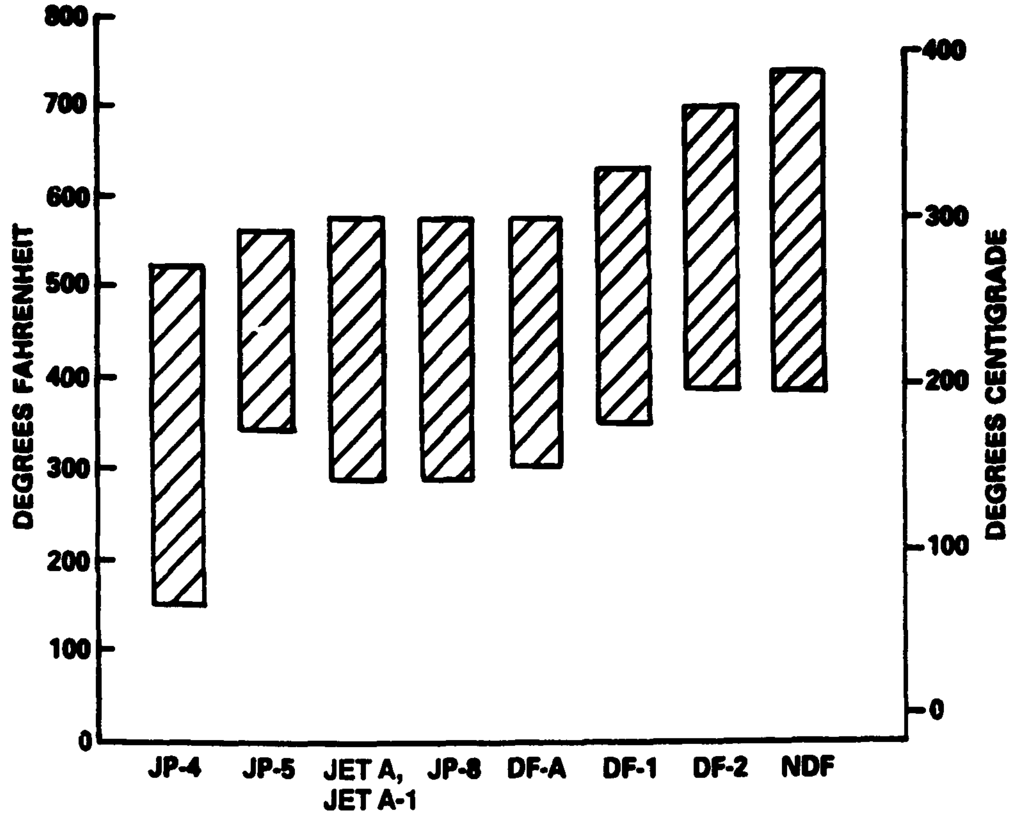


Figure 1. Boiling ranges of fuels

II. OBJECTIVE

The objective of this investigation was to determine the cause of premature failure of five Stanadyne Model DB rotary fuel injection pumps that were operated with Jet A-1 aviation fuel.

III. EXPERIMENTAL APPROACH

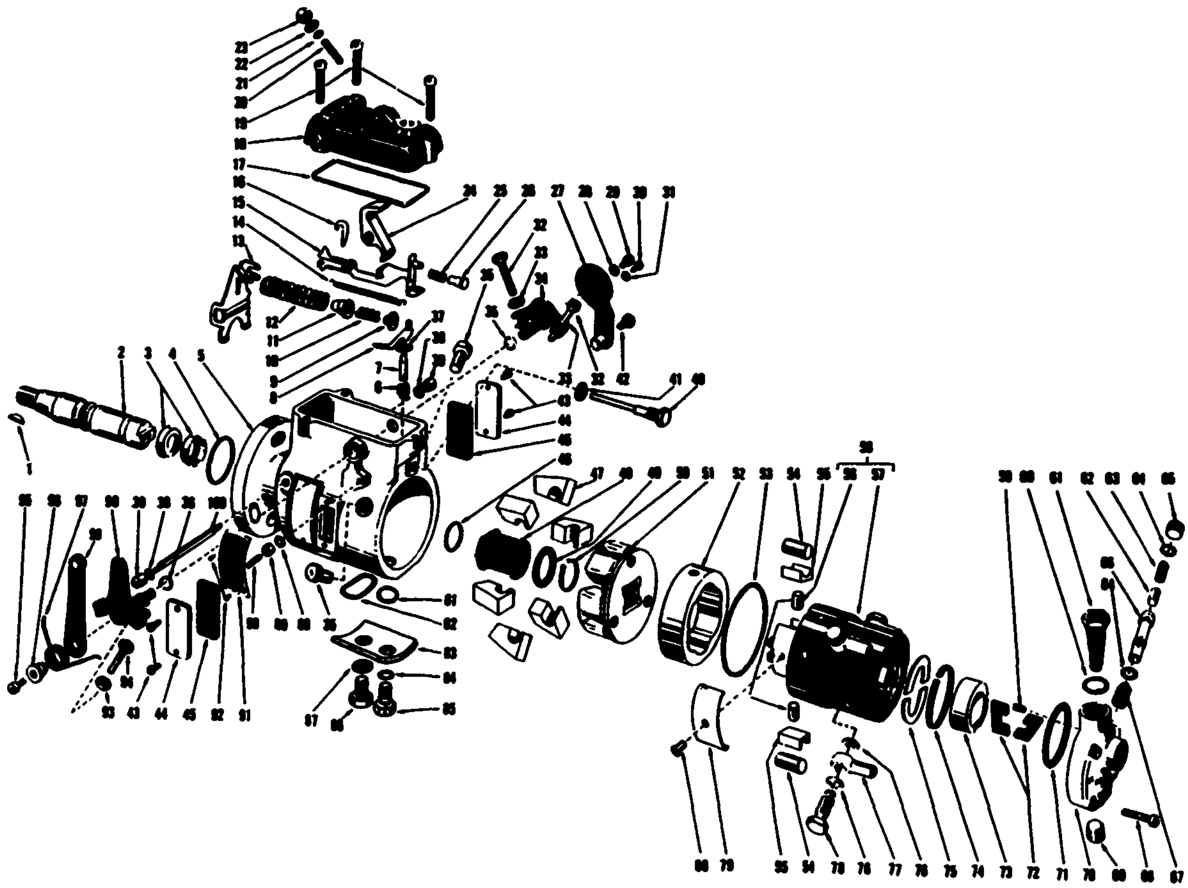
The five pumps received by BFLRF were identified only by the manufacturer, model number and serial number stamped on each unit. Little background information was available other than the Stanadyne Model DB rotary fuel injection pumps had been used on Army diesel engine driven mobile power generator sets in Operation Desert Shield. The identification numbers associated with each pump are summarized in TABLE 2.

TABLE 2. Summary of Identification Numbers Associated With Each Pump

Pump No.	Serial No.	Model No.	AL No.
1	5545723	DBMFC 629-2LQ	AL-19573-X
2	6192152	DBMFC 2605	AL-19574-X
3	5258129	DBMFC 6331LK	AL-19577-X
4	6192153	DBMFC 2605	AL-19575-X
5	6192664	DBMFC 633-2604	AL-19576-X

An exploded view of the Stanadyne DB pump may be seen in Fig. 2. The manufacturer describes this pump as a single-cylinder, opposed plunger, inlet metering, distributor type. Power is transmitted to the pump by a removable drive shaft connected to the pump rotor through a drive tang. A weak point is provided in the drive shaft to protect the engine in case of pump seizure. Fuel is drawn into the unit by a positive displacement, vane-type transfer pump. During normal operation, a precisely metered volume of fuel passes from the transfer pump to the hydraulic head at relatively low pressure of less than 130 psi. The volume of fuel transferred is defined by a metering valve, the position of which is determined by the throttle setting and a centrifugal governor. Fuel is forced from the hydraulic head at high pressure by two plungers and is sent to the appropriate injector connection through a distributor rotor. The final component in the pump mechanism is a delivery valve that ensures a sharp fuel cut off at the end of the delivery cycle.

The drive shafts were missing from most of the pumps. Each pump was tested for seizure using the drive shaft from Pump No. 5258129 (AL-19577-X). Pump No. 5545723 (AL-19573-X) had a different drive shaft geometry from the others. As a result, it could not be tested for seizure in this way. One of the pumps appeared to be seized, and several others were excessively stiff. Subsequent examination indicated that the governor weights fall from their retainer when the drive shaft is removed (this may be prevented if the throttle is held in the wide open position). The weights then bind with the mechanism, making the pump appear seized.



1. KEY, drive shaft
2. SHAFT, drive
3. SEAL, drive shaft
4. SEAL, pilot tube
5. HOUSING ASSEMBLY, pump
6. SPRING, metering valve
7. VALVE, metering
8. ARM ASSEMBLY, metering valve
9. GUIDE, idling spring
10. SPRING, idling
11. RETAINER, spring
12. SPRING, governor control
13. ARM, governor
14. SPRING, governor linkage
15. HOOK ASSEMBLY, governor linkage
16. CAM, shut-off
17. GASKET, control cover
18. COVER, governor control
19. SCREW, cover hold-down
20. SCREW, low idle adjusting
21. SEAL, low idle adj. screw
22. WASHER, low idle adj. screw
23. NUT, low idle adj. screw
24. LEVER, throttle shaft
25. SPRING, damper
26. SLEEVE, damper
27. LEVER ASSEMBLY, adj. shut-off
28. LOCKWASHER, adj. shut-off lever ret. screw
29. SCREW, adj. shut-off lever retaining
30. SCREW, adj. shut-off lever positioning
31. LOCKWASHER, adj. shut-off lever pos. screw
32. SCREW, shut-off lever adjusting
33. NUT, adjusting screw
34. SHAFT ASSEMBLY, shut-off
35. SCREW, head locking
36. SEAL, shaft
37. SHIM, metering valve
38. SEAL, pivot shaft
39. NUT, pivot shaft retainer
40. STUD, guide
41. WASHER, guide stud
42. SCREW, stop lever fitting
43. SCREW, timing line cover
44. COVER, timing line
45. GASKET, timing line cover
46. RING, drive shaft retaining
47. WEIGHT, governor
48. SLEEVE, governor thrust
49. WASHER, governor sleeve thrust
50. RING, governor cage retaining
51. RETAINER ASSEMBLY, governor weight
52. CAM RING
53. SEAL, hydraulic head
54. ROLLER, cam
55. SHOE, cam roller
56. PLUNGER, rotor
57. HEAD AND ROTOR, hydraulic
58. HYDRAULIC HEAD AND ROTOR ASSEMBLY
59. ROLLPIN, end plate locating
60. SEAL, filter cap
61. CAP & FILTER ELEMENT ASSEMBLY
62. PISTON, regulating
63. SPRING, regulating
64. SEAL, end plate sleeve
65. PLUG, end plate
66. SLEEVE, end plate
67. SPRING, plunger retaining
68. SCREW, end plate
69. PLUG, end plate pipe
70. PLATE, end
71. SEAL, transfer pump
72. BLADE, transfer pump
73. LINER, transfer pump
74. RING, rotor retainer
75. RETAINER, rotor
76. WASHER, fuel line connector screw
77. CONNECTOR, fuel line
78. SCREW, fuel line connector
79. SPRING, leaf
80. SCREW, leaf spring adjusting
81. SEAL, head locating screw
82. SEAL, cam hole
83. PLATE, cam locating
84. SEAL, head locating screw
85. SCREW, head locating
86. SCREW, cam locating
87. WASHER, cam locating screw
88. SEAL, torque screw
89. NUT, torque screw
90. SCREW, torque
91. PLATE, name
92. SCREW, name plate
93. NUT, high idle adjusting screw
94. SCREW, high idle adjusting
95. SCREW, throttle lever retaining
96. RETAINER, throttle lever spring
97. SPRING, throttle lever
98. LEVER ASSEMBLY, throttle shaft
99. SHAFT ASSEMBLY, throttle
100. SHAFT, governor arm pivot

Figure 2. <u>Exploded view of the Stanadyne model DB rotary fuel injection pump</u>
(Note: This figure was taken from the Stanadyne operation and instruction manual.)

An evaluation of Stanadyne Model DB2 rotary fuel injection pumps, which are used in the Commercial Utility Cargo Vehicle (CUCV) and the High Mobility Multipurpose Wheeled Vehicle (HMMWV), was conducted running on JP-8 fuel.(10) In this evaluation, it was found that drive tang wear in the fuel pump contributed to a loss in performance. Only one complete drive assembly was provided with the present batch of pumps, making it impossible to reevaluate this wear mechanism.

In most instances, the cause of failure may be determined by careful examination of the used pump and may typically be attributed to one of the following causes:

a. Dirty fuel
b. Excessive hydraulic loading on the transfer pump
c. Misalignment between the drive and the pump
d. Plugging of discharge lines or injectors
e. Corrosion (moisture).

In the present study, the additional effects of low fuel lubricity must also be considered. A range of contact and materials conditions coexist within the pump. The rotor is hydrodynamically suspended on a thin film of liquid, the properties of which are affected by fuel viscosity. By comparison, the plunger/cam assembly in the hydraulic head is highly loaded and is likely to depend on boundary/elastohydrodynamic (EHD) lubrication between the opposing surfaces.

Because of the possible range of lubrication and failure mechanisms in each pump, careful disassembly was required. In particular, all internal surfaces within the pump were rinsed with iso-octane during disassembly and the solvent collected for examination. If the cause of failure was not obvious on disassembly (i.e., the pump was not seized), the pump was placed on a test stand, and its delivery characteristics were compared with the manufacturer's specifications.

IV. DISCUSSION OF RESULTS

A. Disassembly and Failure Analysis

1. Pump No. 1

Number: AL-19573-X
Model No: DCMFC 629-2LQ
Serial No: 5545723
Outlet Ports: 6
Remarks:
a. All the fuel ports were exposed
b. The drive shaft was sheared.
c. The pump was tagged with:
60 kW
Model No. MEP006A
Serial No. F20090
Registration No. N/A
WO No. A044492
Hours: 414

This pump was received with the drive shaft and drive gear in place. The pump rotor was seized within the hydraulic head, and the shaft was sheared. To allow complete disassembly, the pump lining was pressed from the hydraulic head and sectioned parallel to the axis of the seized rotor. Seizure between the rotor and the hydraulic head occurred at a point close to the transfer pump, as shown in Fig. 3.

In running the engine with diesel fuel, seizure at this position normally indicates that excessive side thrust is occurring at the transfer pump, due either to mechanical or hydraulic loading. Such loading is normally caused by one of the following:

a. Excessive transfer pump pressure (maladjustment, over-speed, misalignment)
b. Tight transfer pump blades
c. Broken transfer pump blades
d. Over tightened end plate screws on the transfer pump.

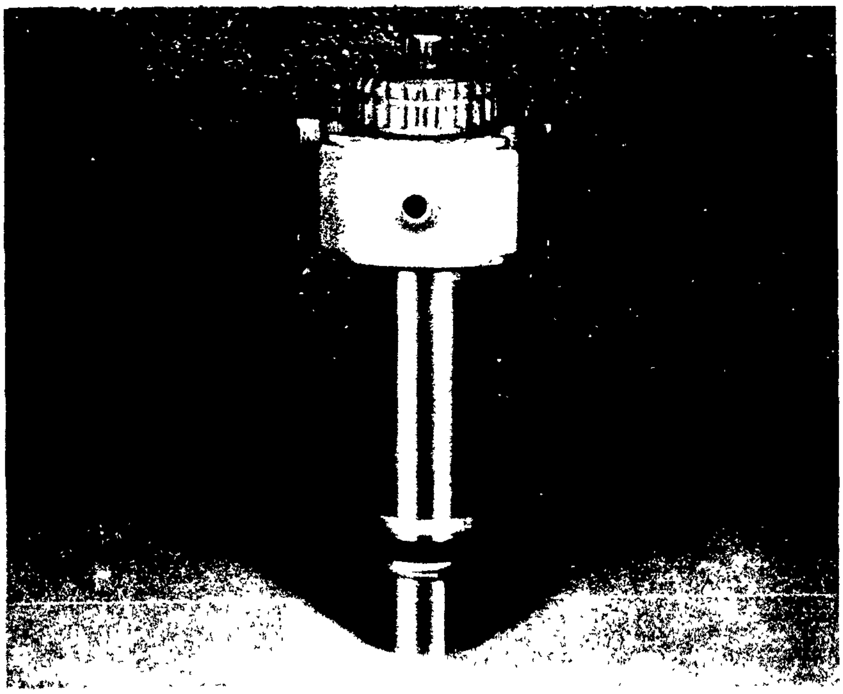
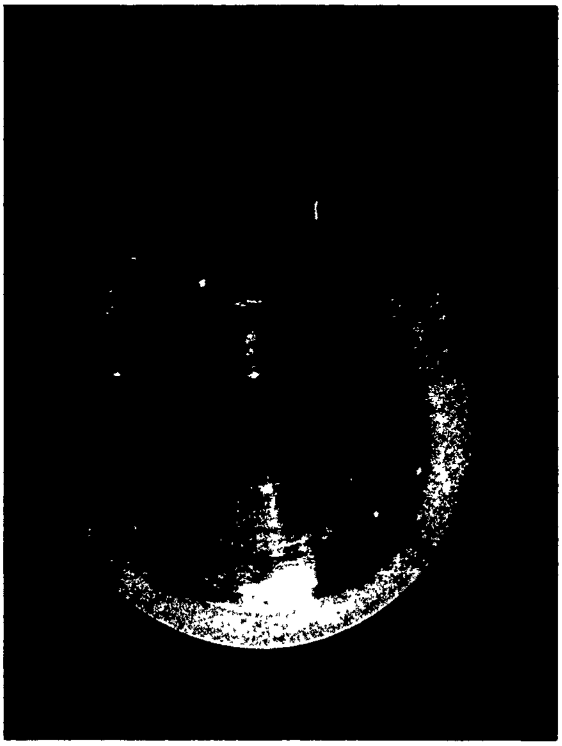


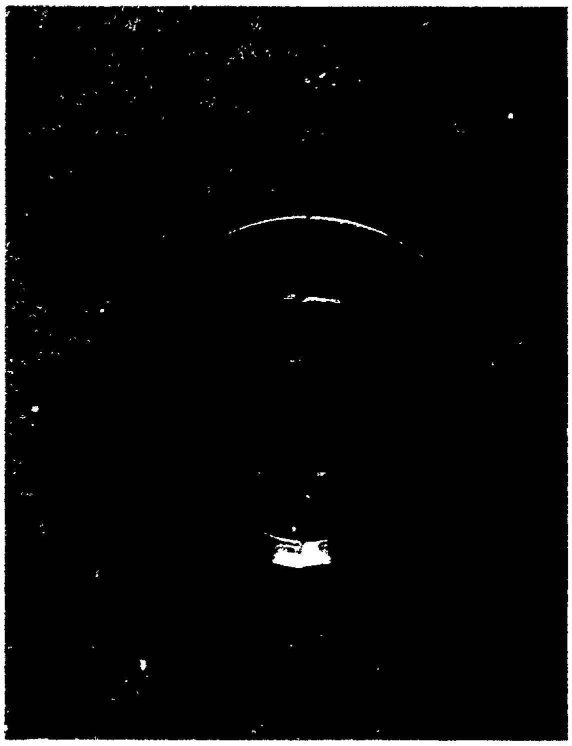
Figure 3. **Rotor from Pump No. 5545723**
[Note: Abraded ring caused by seizure (close to transfer pump at the bottom of the picture).]

Subsequent examination revealed high wear at both ends of the transfer pump on the outlet side, as shown in Fig. 4a and 4b. The crescent-shaped wear scar was relatively deep and confined to a small area towards the outside of the circle swept by the blades. The shape of the scar indicates that it was probably due to some form of misalignment within the pump assembly. In addition, the spring between two of the four transfer pump blades was broken, indicating a serious problem in this area of the pump.

Some shiny debris was found inside the pump. X-ray analysis (EDAX) indicates that this debris is mainly iron and calcium. The iron was probably produced by the formation of wear particles during seizure, while the source of the calcium deposit is less clear. Analysis of sand from Saudi Arabia indicates that it is formed largely from calcium. However, sand normally contains an appreciable amount of silicon, which was not found in the present analysis. Contamination of the parts by water either before or after failure may also have introduced calcium deposits.



a. Retainer



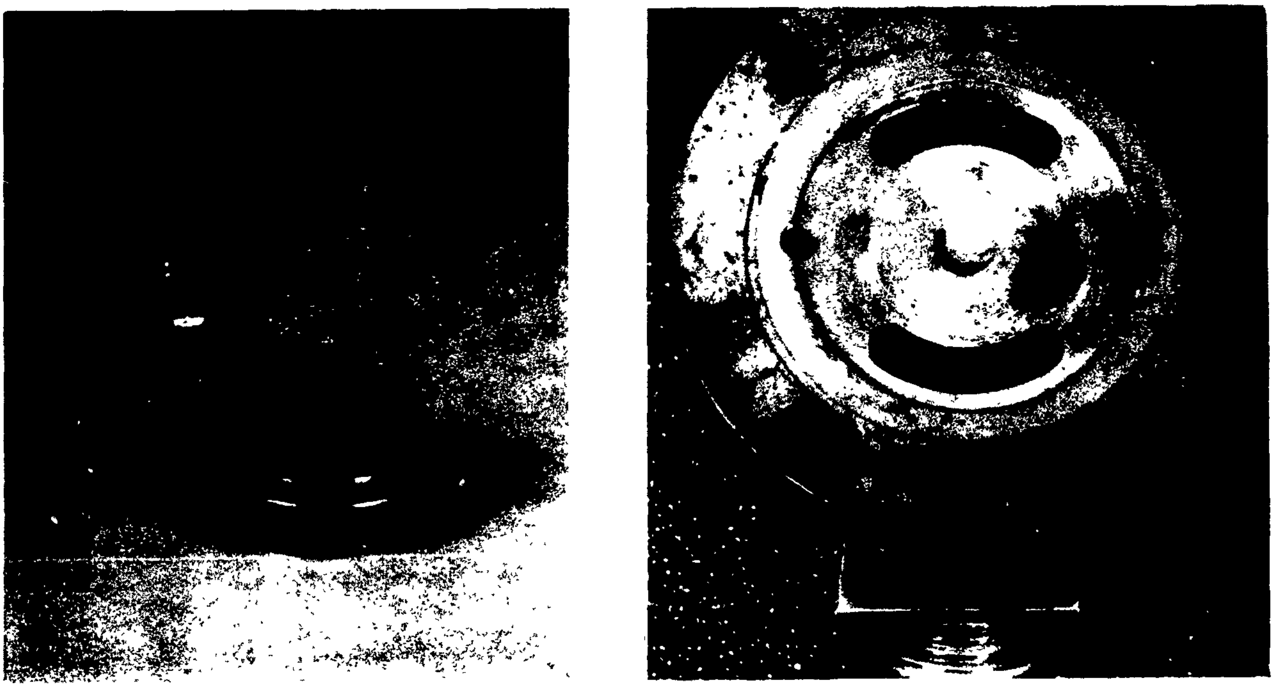
b. Regulator

Figure 4. <u>Worn end pieces from transfer Pump No. 5545723</u>

2. Pump No. 2

Number:	AL-19574-X
Model No:	DBMFC 2605
Serial No:	6192152
Outlet Ports:	4
Remarks:	a. Drive shaft and top cover removed
	b. All fuel ports exposed
	c. Rotor is not seized
	d. Pump tagged with: "Continues to feed fuel after shutdown"

On disassembly, particles and fine debris were found throughout the pump, as shown in Fig. 5, which depicts the cam screw plug and end plate. X-ray analysis (EDAX) of representative particles collected from around the advance piston mechanism confirms that the particles are predominantly ferrous in nature.



a. Cam Screw Plug *b. End Plate*

Figure 5. **Debris on internal parts of Pump No. 6192152**
(Note: The particles are toward the center of the end plate, which is adjacent to the transfer pump.)

Pitting was visible on both the cam ring and rollers, while abrasive scratches were visible in the roller shoes. Surface pitting is a common characteristic in corroded injector pumps, probably due to corrosion-induced fatigue. A scanning electron micrograph of surface damage on one of the rollers is shown in Fig. 6.

Although the rotor was not seized, the pump was not placed on a test stand as the debris within the pump may have caused further damage during operation. The pump was tagged with "continues to feed fuel after shutdown," indicating some problem with the fuel metering system. The metering valve spindle, which controls the fuel supply from the pump, was removed and found to be slightly worn, as shown in Fig. 7. This worn spindle may allow fuel to flow, even in the OFF position. A new oversize metering valve was obtained and was found to fit most of the way into the existing metering valve bore, confirming that the bore is oversize.

Figure 6. SEM micrograph of surface pitting on cam roller from Pump No. 6192152

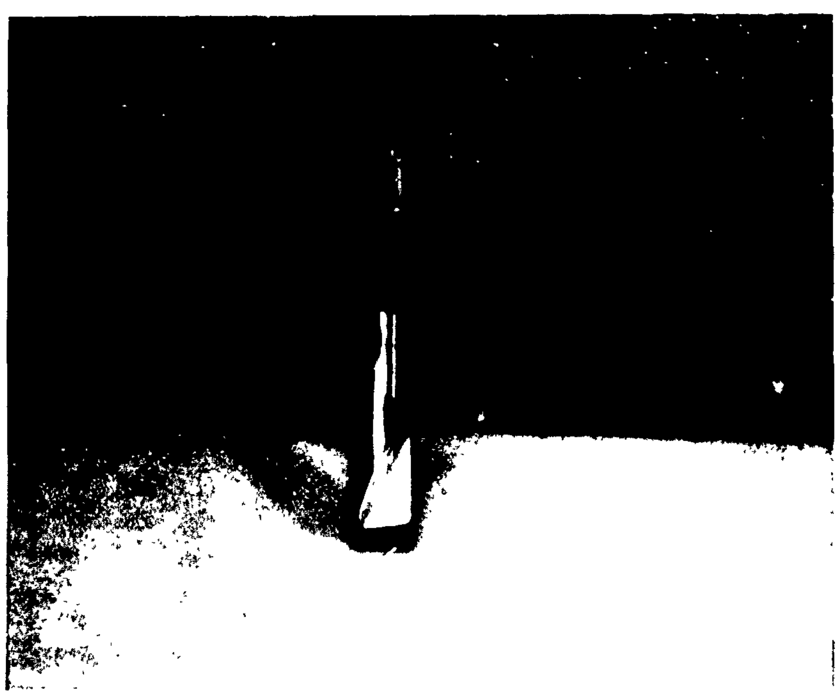


Figure 7. View of the worn surfaces on the metering valve from Pump No. 6192152

3. Pump No. 3

Number: AL-19577-X
Model No: DBMFC 633-1LK
Serial No: 5258129
Outlet Ports: 6
Remarks:
a. Fuel inlet port exposed
b. Fuel outlet ports covered
c. Drive shaft installed
d. Rotor does not appear to be seized
e. Pressure regulator sleeve assembly missing

The rotor on this pump was not seized and could turn freely in the pump housing. The pump was visually inspected inside the governor housing and transfer pump, and no obvious damage or debris was present. As catastrophic failure had not taken place, the pump was placed on a test stand before disassembly to determine the cause of failure.

The pump was operational and met the manufacturer's specifications for both flow rate and timing during normal running. However, the fuel flow rate with the throttle at the off position exceeded the maximum value specified (7 cm^3/1000 strokes vs. 3 cm^3/1000 strokes). This flow resulted in enough fuel to open the injectors on the test stand and may cause run-on in a practical application. The metering valve was removed and found to be free of visible wear. An oversize metering valve would fit freely into the existing bore, indicating that the standard metering valve was too loose. The pump was retested on the stand and perfect operation was restored by the oversize valve.

4. Pump No. 4

Number: AL-19575-X
Model No: DBMFC 2605
Serial No: 6192153
Outlet Ports: 4
Remarks:
a. Drive shaft and top cover removed
b. All fuel ports exposed
c. Rotor binds at a certain position once during each revolution

Although the inlet filter screen was missing, the remainder of the pump appeared new or to have been thoroughly overhauled. Grease used during assembly was still present around a number of O-rings and seals.

The pump rotor was stiff and could be turned only with difficulty. However, seizure had not occurred, so components in contact with the rotor were carefully disassembled to determine the cause of binding. Weights from the governor assembly were found to have slipped from the proper position and were interfering with the rotor. This slippage probably occurred when the drive shaft was withdrawn after the pump was removed from the engine and was not the cause of failure.

Little or no wear was present in the transfer pump on either the eccentric liner or the four blades. As the cause of failure was not evident, the pump was reassembled and placed on a test stand. During testing, the pump was found to pass fuel with the throttle in the off position (6 cm^3/1000 strokes vs. 3 cm^3/1000 strokes). The metering valve spindle was removed and found to be slightly worn. An oversize metering valve fitted approximately half way into the valve bore, indicating that the hole was slightly large.

5. Pump No. 5

Number: AL-19576-X
Model No: DBMFC 633-2604
Serial No: 6192664
Outlet Ports: 6
Remarks:
a. Drive shaft and top cover removed
b. Side cover opened
c. All fuel ports exposed
d. Rotor appears seized

The rotor on this pump was stiff and could be turned only with difficulty. Some wear was visible in the transfer pump on both the blades and the eccentric liner. However, the level of transfer pump wear was not excessive, and the rotor remained stiff after removal of the transfer pump assembly. The rotor became free after removal of the high-pressure head and rotor assembly from the pump housing. Little or no wear was visible in the metering valve or the plunger/cam ring assembly.

As the cause of failure was not evident, the pump was reassembled and mounted on a test stand. However, the pump failed to pass any fluid and was stopped immediately to prevent further damage due to build up of hydraulic head. The delivery valve was removed and found to contain grit. This valve is on the outlet from the pump and had not been removed during the previous inspection. The valve itself was found to be in acceptable condition and was replaced in the pump after cleaning. The pump was retested and found to meet the manufacturer's specifications.

During the initial disassembly and inspection of the pump, it was noticed that the filter element assembly was missing from the inlet to this pump. This assembly may have been unscrewed by accident during removal of the pump from the engine. However, the presence of coarse grit in the delivery valve would indicate otherwise.

B. Detailed Examination of the Metering Valves

Failure of the metering valve to stop fuel flow in the off position occurred in three of the five pumps. For this reason, the metering valves were selected for a more detailed examination. The metering valve consists of a spindle with a helix machined into one side, as shown in Fig. 7. The position of the helix relative to an orifice in the bore determines the fuel supply rate. If the valve spindle is rotated so that the helix is away from the bore, the fuel supply from the transfer pump to the hydraulic head is stopped. Some fuel will normally leak around the valve spindle in the off position (3 cm^3/1000 strokes maximum). However, if the clearance between the valve and the bore is excessive, enough fuel may pass to cause the injectors to open, allowing the engine to run-on.

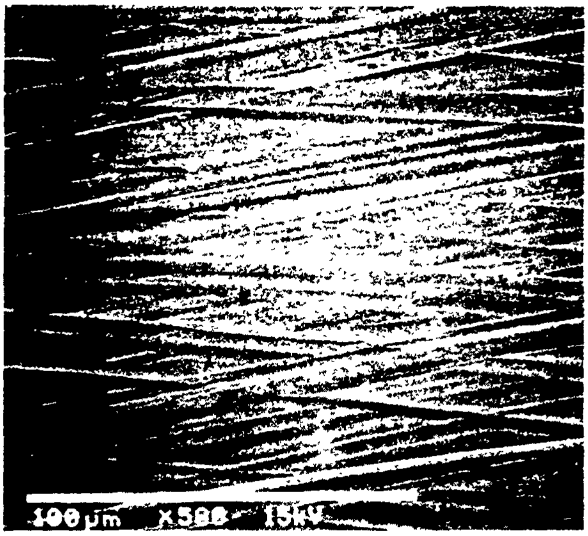
Critical dimensions measured from each of the metering valve components are given in TABLE 3.

TABLE 3. Results From Measurements on Metering Valves

Serial Nos.	Diameter: Valve, inches	Diameter: Bore, inches	Diameter: Bore Roundness, in.	Roughness: Spindle, μ inches	Roughness: Bore, μ inches
5545723	0.2485	0.2498	± 0.0001	6.9	10.8
6192152	0.2484	0.2501	± 0.0000	12.3	9.1
5258129	0.2485	0.2506	± 0.0000	12.3	8.9
6192153	0.2486	0.2502	± 0.0001	10.0	8.5
6192664	0.2485	0.2498	± 0.0000	6.8	12.0
Oversize Valve	0.2500	-	-	6.6	-

The surface roughness was measured using a Talysurf 10 at a filter cut off length of 0.03 inch (0.076 cm). The tabulated value is the average of two readings taken parallel to the axis of the valve. The surface roughness of the valve spindle on Pump Nos. 2, 3 and 4 (all of which failed to seal) is greater than either Pump Nos. 1 or 5. The reason for the greater roughness of these parts is unclear, but is unlikely to be related to the use of Jet A-1 fuel, as no deformation was visible when the surface was examined in the Scanning Electron Microscope (SEM). In general, the surface roughness of the worn areas was much less than the remainder of the part. The diameters of both the valve and the bore were also measured for each pump. No variation in diameter was found along the bore, although two of the bores were found to be very slightly out of round. The diameter of each valve spindle was measured at a number of points. Particular attention was given to comparing the diameter at worn and unworn areas. However, no measurable deviation in the diameter of any of the five valve spindles was found.

After completion of the pump tests, the bores fyrom Pump Nos. 2, 3, and 4 were cut from the hydraulic heads and sectioned parallel to the axis of the valve using an electric discharge machine (EDM). Almost no material was lost during the cutting process, and the complete surface of the valve bore was then available for examination. Machining marks were visible on the surface of each bore and valve spindle, as shown in Fig. 8.



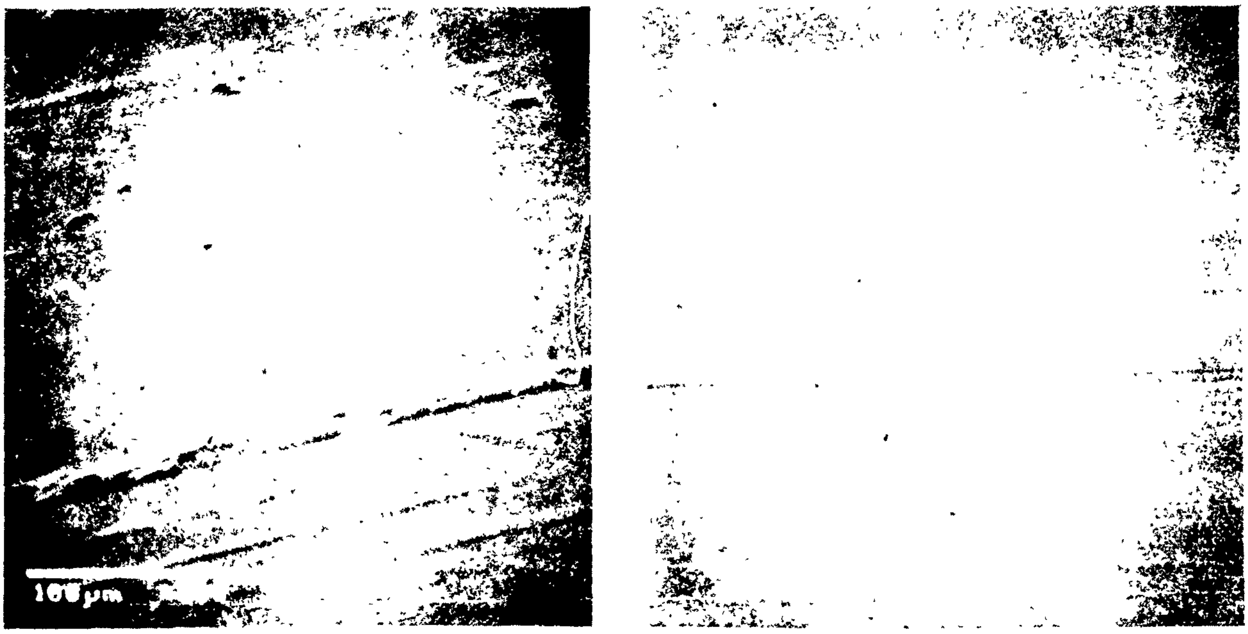
a. *Bore*

b. *Valve spindle*

Figure 8. Representative machining marks on metering valve

Visual examination of the metering valve spindle from Pump No. 2 (Serial No. 6192152) shows areas of wear on the surface close to the helix. The corresponding area on the valve bore is also worn, and the shape of the helix is clearly visible. Although wear of the metering valve is not common, it is occasionally seen in this area close to the helix after extended use (with diesel fuel). Examination of the parts using a scanning electron microscope indicates that the worn areas on both surfaces are highly polished, as shown in Fig. 9a and 9b for the bore and the valve spindle, respectively. The deeper scratches from the machining process are still visible on the bore. No abrasive scratches are visible, and the corrosion that occurred within the remainder of this pump does not appear to have affected the metering valve.

Both the metering valve spindle and the bore from Pump No. 3 (Serial No. 5258129) are free of wear. The spindle has an unidentified thin coating. This coating has the uniform texture shown in Fig. 10 over the complete surface. The normal machining marks are also visible around the entire valve bore. Although it is free of wear, the diameter of the bore is much greater than normal and, as previously stated, will accept an oversize metering valve spindle. The cause of this deviation is unclear. However, it does not appear to be wear related and is unlikely to have been caused by the use of Jet A-1 or JP-8 fuels.



a. Bore *b. Valve spindle*

Figure 9. **Worn surfaces of the metering valve from Pump Serial No. 6192152**

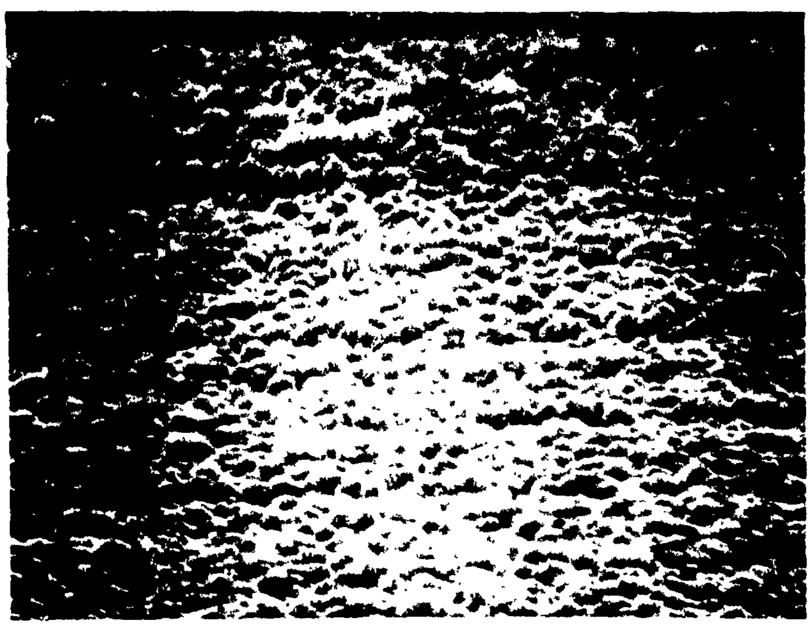


Figure 10. **Surface of coated metering valve spindle (Pump Serial No. 5258129)**

The bore from Pump No. 4 (Serial No. 6192153) also appears unworn, but is slightly bigger than normal (it will almost accept an oversize spindle). The metering valve spindle shows slight wear in two very narrow vertical strips, both of which are away from the helix. Examination of these areas in the scanning electron microscope confirms that the surface is polished and was formed by a mild nonabrasive wear mechanism. The topography of the wear scars is very similar to that seen on the metering valve in Pump No. 2.

The causes of wear on Pump Nos. 2 and 4 are unclear. However, it should be noted that machining marks are still visible on the valve bore, so the wear depth is likely to be less than the surface roughness (<10 micro inch). The amount of material removed from the diameter of the valve spindle could not be measured, but is less than 0.0001 inch. Both of these figures are less than the variation in the bore diameter from pump to pump (± 0.0004 inch), indicating a possible problem during the machining process. This theory is supported by the fact that the metering valve bore in Pump No. 3 is considerably oversize but appears to be completely free of wear. In addition, leakage past a poorly fitting valve is likely to be increased by the use of a low viscosity fuel such as JP-8/Jet A-1.

C. Summary of Pump Wear Characteristics

After completion of the pump stand tests and the complete disassembly of each pump, the wear-prone components were examined, irrespective of the failure mechanism. The majority of these parts did not contribute to the pump failure and would have remained serviceable for some time. In order to define the level of wear, a subjective scale from 0 to 5 was used, with 0 corresponding to no wear and 5 corresponding to component failure or seizure.

The results from this examination are given in TABLE 4. Pump Nos. 1 and 2 were the most severely worn, while Pump No. 3 is almost new. The results for Pump No. 2 are largely influenced by pitting and abrasive wear, probably due to corrosion within the pump and, as such, may not be considered normal wear. Little or no wear was observed around the hydraulic head and rotor assembly on any of the pumps (except for Pump No. 1, which seized due to problems outside this area). In general, significantly more wear was visible in the transfer pump and governor assemblies.

TABLE 4. Subjective Wear Level* on Critical Pump Components

Component		Pump No. 1	2	3	4	5
Hydraulic Head and Rotor	Hydraulic Head	5	1	0	1	1
	Discharge Fittings	0	0	0	0	0
	Distributor Rotor	5	1	0	1	1
	Delivery Valve	3	3	0	1	3
	Plungers	1	0	0	0	1
	Cam Rollers & Shoes	1	2	1	1	1
	Leaf Spring and Screws	1	1	0	0	0
	Cam	0	4	0	0	0
	Govemor Weight Ret.	1	3	0	0	3
	Govemor Weights	0	0	0	0	0
	Govemor Thrust Washer	2	2	0	1	1
	Govemor Thrust Sleeve	1	1	0	0	0
Transfer Pump	End Cap	0	2	0	0	0
	Inlet Screen	1	4	NA	NA	NA
	End Plate Adj. Plug	0	4	NA	0	0
	Regulating Piston	3	4	NA	1	1
	Regulator	4	3	2	2	1
	Blades	2	3	1	1	1
	Liner	3	3	3	4	2
	Rotor Retainers	3	3	1	2	2
Govemor	Pivot Shaft	2	3	1	2	2
	Arm	1	1	0	0	0
	Metering Valve	3	4	0	1	1
	Metering Valve Arm	1	1	0	0	1
Advance	Piston	2	4	0	1	1
	Cam Advance Screw	2	2	0	0	0
	Plugs	0	2	0	0	0

* 0 = no wear; 5 = failure.
NA = Parts were not available when pump was received at BFLRF.

Note: Pump No. 1 = Serial No. 5545723
Pump No. 2 = Serial No. 6192152
Pump No. 3 = Serial No. 5258129
Pump No. 4 = Serial No. 6192153
Pump No. 5 = Serial No. 6192664

V. CONCLUSIONS

A. General Conclusions

The failures of Pump Nos. 1, 3, and 4 could be attributed to quality problems during production/rebuild. The metering valve and bore diameters indicate that they were incorrectly matched during asssembly or rebuild. The corrosion found in Pump No. 2 is assumed to have begun prior to its arrival in Saudi Arabia. The failure of Pump No. 5 is assumed to be caused by the use of dirty fuel.

B. Specific Conclusions

Of the five pumps examined, none of the failures could be directly attributed to the use of low lubricity fuel. Indeed, two pumps contained foreign material, and solid particles were proven to be the prime cause of failure in one case.

Most critical components in the pumps suffered relatively mild wear (except for the apparently corroded pump).

It is significant that in Pump No. 3, no wear was visible on the surface of the failed metering valve. In addition, the wear depth on the metering valve spindles/bores appears to be less than the random variation of the bore diameter from pump to pump. This variation may indicate a problem during the manufacturing/reconditioning process.

Wear of the metering valve assembly is occasionally seen after extended operation with diesel fuel. The lower viscosity of Jet A-1 compared to No. 2 diesel fuel (DF-2) is likely to increase leakage past the poorly fitting metering valves, thereby compounding an existing problem.

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